NASA-CR-203582

CALIFORNIA INSTITUTE OF TECHNOLOGY

SEISMOLOGICAL LABORATORY 252-21

February 10, 1997

63

Impact Cratering Calculations
NASA #NAGW 1953

Final Report

October 1, 1989 to September 30, 1996

Thomas J. Ahrens
W. M. Keck Professor of Geophysics
Principal Investigator
telephone# (818) 395-6906
fax# (818) 564-0715, 568-0935
e-mail: tja@gps.caltech.edu

cc: Dr. Patricia Rogers, NASA Headquarters (2)
Ms. Adriene Woodin, NASA Grants Officer (1)
NASA Center for Aerospace Information
S. Kingston/Accounting (letter only)
Sponsored Research
Patent Office
Seismo Lab

PASADENA, CALIFORNIA 91125

I. Research Accomplishments

We have concentrated our research in the following four areas of study:
1) Impact cratering on silicate planetary surfaces
2) Impact of SL9 on Jupiter
3) Impact-induced atmospheric plumes, erosion and blow-off of planetary atmospheres
4) Miscellaneous (impact-induced magnetization of asteroids and deflection and fragmentation of near-Earth asteroids).

1) Impact Cratering

1) Asteroids

Papers

(a) Love, S. G. and T. J. Ahrens, Catastrophic impacts on gravity dominated asteroids, *Icarus*, 124, 141-155, 1996.

(b) O'Keefe, J. D. and T. J. Ahrens, 1993, Planetary cratering mechanics, J. Geophys. Res., 98, 17011-17028.

(c) O'Keefe, J. D. and T. J. Ahrens, 1994, Impact-induced melting on planetary surfaces in Large Meteorite Impacts and Planetary Evolution, ed. by B. O. Dressler et al., pp. 103-109, Geol. Soc. Am. Spec. Paper 293, Boulder, CO.

(d) Love, S.G. and T. J. Ahrens, Origin of asteroid rotation rates in catastrophic impacts, *Nature*, in press, 1997.

(e) Keil, K., D. Stöffler, S. G. Love, and E. R. D. Scott, Constraints on the role of impact heating and melting in asteroids, *Meteoritics and Planetary Science*, in press, 1997.

Abstracts

(f) O'Keefe, J. D., and T. J. Ahrens, Planetary strength, central peak oscillation, and formation of complex craters, *(abstract)*, in *Lunar Planet. Sci., XXVII*, 983-984, Houston, TX, 1996.

(g) O'Keefe, J. D. and T. J. Ahrens, The role of central peak oscillation in the formation of complex planetary craters, *(abstract)*, in *Lunar Planet. Sci., XXVI*, 1081-1082, Houston, TX, 1995.

(h) Love, S. G., Catastrophic Impacts in the gravity regime, *(abstract), Lunar and Planet. Sci., XXVII*, 777-778, Houston, TX, 1996.

(i) Ahrens, T. J. and S. G. Love, Strength versus gravity dominance in catastrophic impacts, *(abstract)*, in *Lunar Planet. Sci., XXVII*, 1-2, Houston, TX, 1996.

(j) Love, S. G. and T. J. Ahrens, Gravity dominance in catastrophic impacts into asteroids, *(abstract)*, in *Asteroids, Comets and Meteors, Conf.* Versailles, France, July 8-12, 1996.

The asteroids evolve through mutual collisions. Present understanding of asteroid collisions is based largely on laboratory impact experiments employing cm-sized targets whose collisional behavior is determined by material strength (e.g. Davis et al. [1994]; Fujiwara et al. [1989]; Holsapple and Schmidt [1987]; Benz and Asphaug [1994]). Recent calculations (e.g., Asphaug and Melosh [1993]; Holsapple [1994]; Benz et al. [1994]), however, suggest that the collisional breakup of silicate bodies more than a few km in diameter is controlled by gravity rather than strength.

Love and Ahrens [1996a] (paper a), studied impact behavior of gravity dominated asteroids using our three-dimensional Smoothed Particle Hydrodynamics (SPH) code. We studied 3-7 km/sec impacts onto strengthless silicate targets 10 to 100 km in diameter at encounter angles of 15-75°. The catastrophic threshold (impact energy per unit target mass required to permanently remove 50% of the target) ranges from 8×10^3 J kg^{-1} at 10 km diameter to 1.5×10^6 J kg^{-1} at 1000 km, varying as target diameter to the 1.13 ± 0.01 power. Extrapolating these results suggests that gravity dominance extends to stony bodies as small 250 ± 150 m in diameter smaller than previously believed. This result implies that "rubble pile" asteroids may be as small as a few hundred meters across.

Nearly catastrophic impacts can exhume target core material and catapult surface rocks to the antipodes ("scrambling" the target).

We have just completed a study of asteroid rotation rates. These are deduced from observed periodic fluctuations in reflected brightness. These are controlled by mutual impacts. Asteroid spin and collisional history heretofore have been linked by analogy to experimental impacts on cm-scale targets cohering by material strength. Recent work, however, questions the analogy for objects the size of most observed asteroid ($\geq$ 1 km in diameter), where gravity rather than strength controls impact response. We developed new computer models of impacts on gravitating bodies which explain some observed rotational properties of asteroids. "Catastrophic" collisions ejecting ~50% of an asteroid's mass dominate spin evolution. The remnant of an initially nonrotating silicate asteroid suffering such an impact rotates at a rate of ~2.9 day^{-1}, comparable to the mean asteroid value of ~2.5^{-1}. Our calculations suggest that the observed trend in mean spin frequency from C (2.2 day^{-1}) to S (2.5 day^{-1}) to M (4.0 day^{-1}) class asteroids arises from increasing density rather than strength. The fraction of projectile angular momentum retained by asteroid targets is low and variable compared to laboratory-scale experiment. A paper (d) [Love and Ahrens, 1997] describing this work has just been accepted by *Nature*.

We have considered fundamental observations from terrestrial impact craters, combined with results from laboratory shock experiments and theoretical considerations, to evaluate the efficiency of impact heating and melting of asteroids. Results: Studies of terrestrial impact craters and relevant shock experiments suggest that impact heating of asteroids will produce two types of impact melts: (1) large scale whole rock melts (total melts, not partial melts) at high shock pressure and (2) localized melts formed at the scale of the mineral constituents (mineral-specific or grain boundary melting) at intermediate shock pressures. The localized melts form minuscule amounts of melt that quenches and solidifies in situ, thus preventing it from pooling into larger melt bodies. Partial melting as defined in petrology has not been observed in natural and experimental shock metamorphism and is thermodynamically impossible in a shock wave-induced transient compressions of rocks. The total impact melts produced represent a minuscule portion of the displaced rock volume of the parent crater. Internal differentiation by fractional crystallization is absent in impact melt sheets of craters of sizes that can be tolerated by asteroids, and impact melt rocks are usually clast-laden. Thermal metamorphism of country rocks by impact is extremely minor. Experimental and theoretical considerations suggest that single, disruptive impacts cannot raise the average global temperature of strength- or gravity-dominated asteroids by more than a few degrees; cumulative global heating of asteroids by multiple impacts is ineffective for asteroids less than a few hundred km in diameter; small crater size, low gravity and low impact velocity suggest that impact melt volume in single asteroidal impacts is a very small (~ 0.01-0.1%) fraction of the total displaced crater volume; total impact melt volume formed during the typical lifetime of an asteroid is a small fraction (<0.001) of the volume of impact-generated debris; much of the impact melt generated on asteroidal targets is ejected from craters with velocities > escape velocity and, thus, not retained on the asteroid. The inescapable conclusion from these observations and calculations is that impacts cannot have been the heat source for the origin of the meteorite types listed above, and recourse must be taken to processes other than impact, such as decay of short-lived radionuclides or electromagnetic induction during an early T tauri phase of the Sun, to explain heating and melting of the parent bodies of these meteorites. A paper [Keil et al., 1997] (e) describing this work is in press in *Meteoritics and Planetary Science*.

2) Solid Planets

In O'Keefe and Ahrens [1993; 1994; 1995] (b, c, f, and g) we report the evolution of the depth, diameter, and crater lip height of transient craters, as well as gravitational collapse of large craters as a function of density, crustal strength, planetary gravity, and impact velocity. We chose this speed to minimize vaporization. We have conducted calculations to a previously unprecedented real time of 32 minutes for a 10 km, diameter/projectile impacting the Earth at 12 km/sec.

We have continued our studies of central peak oscillations from large impacts on planetary surfaces for different values of planetary gravity, crustal strength, including the effect of a Mohr-Coulomb strength models. We have studied the relation of ringed-crater dimensions in terms of impactor size and energy.

2) Impact of SL9 on Jupiter

(a) Ahrens, T. J., T. Takata, J. D. O'Keefe, and G. S. Orton, Impact of Comet Shoemaker-Levy 9 impact on Jupiter, *Geophys. Res. Lett.*, 21, 1087-1090, 1994.

(b) Ahrens, T. J., T. Takata, J. D. O'Keefe, and J. D. Orton, Radiative signatures from impact of Comet Shoemaker-Levy 9 on Jupiter, *Geophys. Res. Lett.*, 21, 1551-1553, 1994.

(c) Takata, T., J. D. O'Keefe, T. J. Ahrens, and G. S. Orton, Comet Shoemaker-Levy-9: Impact on Jupiter and plume evolution, *Icarus,* 109, 3-19, 1994.

(d) Takata, T., Three-dimensional analysis of impact processes on planets, Ph. D. thesis, California Institute of Technology, 1995.

(e) Takata, T., T. J. Ahrens, and A. W. Harris, Comet Shoemaker-Levy 9: Fragment and progenitor impact energy, *Geophys. Res. Lett.*, 22, 2433-2436, 1995.

(f) Roulston, M. and T. J. Ahrens, Impact mechanics and frequency of SL9-type events on Jupiter, *Icarus*, [in press], 1997.

(g) Takata, T., T. J. Ahrens, Impact of Comet Shoemaker-Levy 9 - Size, origin, and plumes - Comparison of numerical analysis with observations, *Icarus*, [in press], 1997.

(h) Ahrens, T. J., T. Takata, J. D. O'Keefe, Comet Shoemaker-Levy 9 impact on Jupiter, in Shock Waves, Proc. 20 Int. Shock Waves Symp., ed. by B. Sturtevant, J. E. Shepherd, and H. G. Hornung, Vol. 2, 1455-1460, 1997, World Scientific, Singapore.

When fragments of SL9 impacted Jupiter in July 1994 the plumes were observed to rise to altitudes of about 3000 km above the 1-bar level with a variation of 25 percent. We have addressed why the plume heights differed by only a factor of 0.75, whereas the energy of the fragments differed by more than a factor of 20, in papers based on analytical and numerical methods (Roulston and Ahrens [1997] and Takata and Ahrens [1997]).

Before the collision of SL9 with Jupiter, several groups used finite element hydrodynamic models to predict the depth of penetration and the energy deposition profile in the Jovian atmosphere [Crawford et al., 1994; MacLow and Zahnle, 1994; Takata et al., 1994]. These models assumed that the weakness of comets in general, and SL9 in particular, inferred from the magnitude of disruptive tidal forces [Scotti and Melosh, 1993]. The formation and growth of hydrodynamic instabilities was the most important process in the breakup of impactors. In Roulston and Ahrens [1997], a semi-analytic model for the breakup of SL9 by hydrodynamic instabilities is developed. This model has implications for the effect of resolution of numerical models on penetration depth, in agreement with MacLow and Zahnle [1994]. Roulston and Ahrens [1997], explain that the reason plume heights were similar was because the energy deposited per unit mass is independent of impactor diameter. This paper expands on an explanation given by Crawford et al. [1995]. Thus the plumes produced by fragments A, E, and W, which were thought to have masses varying by a factor of 20 based on Hubble Space Telescope (HST) observations [Weaver et al., 1995], had nearly identical heights of 3000 km above the 1-bar level [Hammel et al., 1995]. The plume heights imply that for these impacts, the vertical velocity in the plumes was about 12 kms^{-1}. From our theoretical analysis, we inferred that fragments A, E, G, and W all had diameters exceeding 0.3 km and this lower limit on their diameter is used to obtain a lower limit of 1.6 km diameter for the progenitor comet.

This agrees with the results of Scotti and Melosh [1993], Asphaug and Benz [1994] and Solem [1994] who calculated progenitor diameters of 2.0, 1.6, and 1.8 km. We also calculated that the expected intervals between impacts of 0.3 km and 1.6 km diameter objects on Jupiter are about 500 and 6000 years, respectively.

3) Effects of Large-Impacts on the Atmosphere

Papers

(a) Newman, W. I., E. M. D. Symbalisty, T. J. Ahrens, E. M. Jones and A. J. Chaikin, Impact events and the erosion of planetary atmospheres: Some surprising results from theory and simulation, *Icarus*, [submitted], 1997.

(b) Evans, N., T. J. Ahrens, and D. C. Gregoire, Fractionation of Ruthenium from Iridium at the Cretaceous-Tertiary Boundary, *Earth Planet. Sci. Lett.*, 134, 141-153, 1995.

(c) Chen, G. Q. and T. J. Ahrens, Erosion of terrestrial planet atmosphere by surface motion after a large impact, *Physics of Earth & Planetary Interiors*, [submitted], 1996.

Abstracts

(d) Newman, W. I., and T. J. Ahrens, Blast waves and the blow-off effect in terrestrial atmospheres, *(abstract)*, in *Lunar & Planet. Sci., XXVI*, pp. 1041-1042, Houston, TX, 1995.

(e) Chen, G., and T. J. Ahrens, Calculation of shock wave in a gravity-bound, spherical atmosphere, *(abstract)*, in *20th Intl. Symp. on Shock Waves*, Pasadena, CA (July 23-28, 1995), 1995.

(f) Newman, W. I., E. M. D. Symbalisty, E. M Jones and T. J. Ahrens, Impact events and the erosion of planetary atmospheres: Some surprising results from theory and simulation, *(abstract)*, in *Lunar Planet. Sci., XXVII*, 955-956, Houston, Tx, 1996.

(g) Farley, K. A., S. G. Love, and D. B. Patterson, Atmospheric entry heating and helium retentivity of interplanetary dust particles, *Geochim. Cosmochim. Acta*, submitted, 1997.

Large (10^{31} to 10^{35} erg), impacts couple most of their energy directly to the Earth. It is the Earth moving up and down in response to strong ground motion from Rayleigh waves that drives energy into the atmosphere [Ahrens, 1993]. This problem was approximately treated in Ahrens [1993]. Recently, Chen and Ahrens [1996] (paper c) rewrote Kipp and Lawrence's [1982] one-dimensional Lagrangian compressible finite-difference code to include gravity to study this blow-off phenomena in the atmosphere.

We have modeled atmospheric entry heating of interplanetary dust to characterize the population of particles carrying extraterrestrial helium to the seafloor. We find that ~0.5% of the mass and ~4% of the surface area of the infalling dust transits the atmosphere at temperatures lower than that required for He release (~600°C). Size-dependent heating causes the particles which retain He to be far smaller than those in the parental interplanetary dust population. The particle-size distribution of He-bearing dust is such that most of the mass is delivered by particles of ~20 μm diameter, while most of the surface area (relevant for surface-correlated constituents, e.g., implanted solar wind He) is carried by particles of ~7 μm diameter. Knowledge of these size distributions allows us to evaluate the possibility of sedimentary redistribution of extraterrestrial dust in the atmosphere and ocean. The size distributions also have important consequences for interpretation of He abundances in seafloor sediments samples that integrate over fairly small areas and times. Sediment samples generally will not record a representative distribution of interplanetary dust, but will have a strong tendency to undersample rare large particles. We predict a high degree of variability in replicate He analyses of a single sediment sample, with a mass-correlated He component yielding greater variability than a surface-correlated component. Comparison with sediment measurements confirms such variability of demonstrates excellent agreement with the statistical distribution expected for a surface correlated component, consistent with suggestions that seafloor extraterrestrial He is surface-correlated implanted solar wind or solar flare helium. A second important statistical effect is that sediment measurements systematically underestimate the true extraterrestrial He flux, typically by a factor of two. We have submitted a paper to *Geochim. Cosmochim. Acta*, 1997 [Farley et al., 1997].

4) Miscellaneous

(a) Chen, G., R. Hide, and T. J. Ahrens, Hypervelocity impacts and the magnetism of small bodies in the solar system, Icarus, 115, 86-96, 1996.

(b) Ahrens, T. J. and A. W. Harris, Deflection and fragmentation of near-earth asteroids, in Hazards due to Comets and Asteroids, edited by T. Gehrels and M. Matthews, pp. 897-927, U. Arizona Press, Tucson, 1995.

(c) Ahrens, T. J. and A. W. Harris, Deflection and fragmentation of near-Earth asteroids, *Nature*, 360, 429-433, 1992.

(d) Bottke, W. F., Jr., D. C. Richardson, and S. G. Love, Can tidal disruption of asteroids make crater chains on the Earth and Moon? submitted, 1997.

The main new approach in Chen et al. [1995] is that we assume that the magnetization of S asteroids, Gaspra and Ida, result from magnetized kaemacite (nickel-iron) distributed throughout a largely silicate object. We examined the question as to whether a large portion of a proto-asteroid could be shocked to sufficiently high pressure such that the iron grains within the asteroid are driven out of the α-iron (ferromagnetic) phase either into the non-magnetic region of the α-phase (above the Curie point) or into the γ- or ε-iron (non-magnetic phase regimes) depending on asteroid porosity. Here we utilize our previous results [Ahrens and O'Keefe, 1977] of impact-induced shock attenuation to determine the decrease in shock pressure with radius from the impact for differing impactor speeds. Upon subsequent rarefaction (unloading) the iron is assumed to take on the ambient solar-system or dynamically induced magnetic field. A second constraint is to demonstrate that, a fragment remagnetized in this way, is sufficiently large to comprise its present observed size. Here we use the impact fragmentation theory for asteroids developed by Housen et al. [1991]. We find that Ida and Gaspra could have evolved from proto-asteroids, 125 ± 22 and $45\ \pm15$ km.

The Ahrens and Harris [1995] paper amplifies on our earlier *Nature* article [Ahrens and Harris, 1992] and includes detailed analysis of collisional outcomes of inducing orbit perturbation, a new formulation of impact induced momentum transfer in the strength and gravity regimes. Also included is an analysis of the limits to momentum transfer which can occur upon impact on an asteroid without asteroid destruction.

Tidal disruption of rubble-pile bodies (stony or icy aggregates held together by self-gravity) during close Earth encounters may produce significant numbers of Tunguska-sized (50 m) fragments. Using an N-body simulation to model encounters between strengthless, elongated, rotating, particulate bodies and the Earth, we found two disruption categories which produce small bodies: (a) "Shoemaker-Levy-9 type" catastrophic disruptions, where the progenitor is pulled into a line of similarly-sized bodies, and (b) rotational disruptions, where the progenitor is distorted and spun-up by tidal torque such that particles are ejected along the equator. These events occur frequently at low encounter velocities (i.e. low e and i); we predict that Earth's tidal forces should be effective at disrupting outcomes for the progenitor's encounter parameters and integrating over all possible values of those parameters, we found the tidal production rate of Tunguska-sized bodies (upper limit) was comparable to the main-belt injection rate of Tunguska-sized bodies into resonant orbits. We conclude that tidal disruption plays an important role in maintaining the steady-state fraction of small Earth-crossing asteroids. We submitted a paper to *Planetary and Space Science* (d) on this work.

Crater chains, presumably formed by weak asteroids or comets stretched apart by planetary tides, have been tentatively identified on both the Earth and Moon. By modeling tidal disruption by the Earth and Moon of "rubble-pile" bodies, we find that the Earth disrupts enough objects over the last 3.8 billion years to account for one or two lunar crater chains, but that the reciprocal production rate of terrestrial crater chains is too low to make any in observable geological history. A short note on this has been submitted to *Icarus* [Bottke, W. F., Jr. et al., 1997].

Manuscripts published, submitted, or in press:

1. Ahrens, T. J., Book Reviews of "The Earth's Core: by J. A. Jacobs, and "The Physics of the Earth's Core" by Paul Melchior, *Physics Today*, *42*, 89-90, 1989.
2. Ahrens, T. J., Water storage in the mantle, *Nature*, *342*, 122-123, 1989.
3. Ahrens, T. J., Is the Earth's interior dissolving?, *Physics World*, *2*, 20-21, 1989.
4. Ahrens, T. J., J. D. O'Keefe, and M. A. Lange, Formation of atmospheres during accretion of the terrestrial planets, in *Origin and Evolution of Planetary and Satellite Atmospheres*, edited by S. K. Atreya, et al., pp. 328-385, U. of Ariz. Press, Tucson, AZ, 1989.
5. O'Keefe, J. D., and T. J. Ahrens, Impact production of CO_2 by Cretaceous/Tertiary extinction bolide and the resultant heating of the Earth, *Nature*, *338*, 247-249, 1989.
6. Ahrens, T. J., Earth Accretion, in *Origin of the Earth*, edited by J. Jones and H. Newsom, pp. 211-227, Oxford U. Press, Oxford, 1990.
7. Ahrens, T. J., Geophysics, in *Encyclopedia of Physics*, 2nd Ed., edited by R. G. Lerner and G. L. Trigg, pp. 436-442, VCH Publishers, 1990.
8. Ahrens, T. J., and A. W. Harris, Deflection and fragmentation of near-Earth asteroids, *Nature*, *360*, 429-433, 1992.
9. Smither, C. L., and T. J. Ahrens, Melting, vaporization, and energy partitioning for impacts on asteroidal and planetary objects, in *Asteroids, Comets, and Meteors 1991*, edited by A. W. Harris and E. Bowell, pp. 561-564, Lunar and Planetary Institute, Houston, 1992.
10. Ahrens, T. J., Chapter 4. Equation of State, in *High Pressure Shock Compression of Solids*, edited by J. R. Asay and M. Shahinpoor, pp. 75-114, Springer-Verlag, New York, 1993.
11. Ahrens, T. J., Impact erosion of terrestrial planetary atmospheres, *Annu. Rev. Earth Planet. Sci.*, *21*, 525-555, 1993.
12. Ahrens, T. J., Weapons of mass protection, *World & I, May*, 216-221, 1993.
13. O'Keefe, J. D., and T. J. Ahrens, Planetary cratering mechanics, *J. Geophys. Res.*, *98*, 17011-17028, 1993.
14. Ahrens, T. J., Origin of the Earth, *Physics Today*, *47*, 38-45, 1994.
15. Ahrens, T. J., and A. W. Harris, Deflection and fragmentation of near-earth asteroids, in *Hazards Due to Comets and Asteroids*, edited by T. Gehrels and M. Matthews, pp. 897-927, U. Arizona Press, Tucson, 1994.
16. Ahrens, T. J., T. Takata, J. D. O'Keefe, and G. S. Orton, Radiative signatures from impact of Comet Shoemaker-Levy 9 on Jupiter, *Geophys. Res. Lett.*, *21*, 1551-1553, 1994.
17. Ahrens, T. J., T. Takata, J. D. O'Keefe, and G. S. Orton, Impact of Comet Shoemaker-Levy 9, *Geophys. Res. Lett.*, *21*, 1087-1090, 1994.
18. O'Keefe, J. D., and T. J. Ahrens, Impact-induced melting on planetary surfaces, in *Large Meteorite Impacts and Planetary Evolution*, edited by B. O. Dressler, et al., pp. 103-109, Geol. Soc. Am. Spec. Pap. 293, Boulder, CO, 1994.
19. Takata, T., J. D. O'Keefe, T. J. Ahrens, and G. S. Orton, Comet Shoemaker-Levy-9: Impact on Jupiter and plume evolution, *Icarus*, *109*, 3-19, 1994.
20. Ahrens, T. J., and K. Farley, Conference explores new research in the deep Earth and planetary volatiles, *Eos, Trans. AGU*, *76*, [19], 195, 1995.
21. Chen, G., T. J. Ahrens, and R. Hide, Hypervelocity impacts and the magnetization of small bodies in the solar system, *Icarus*, *115*, 86-96, 1995.
22. Takata, T., T. J. Ahrens, and R. Phillips, Atmospheric effects on cratering on Venus, *J. Geophys. Res.*, *100*, 23,329 - 23,348, 1995.

23. Ahrens, T. J., Application of shock compression science to Earth and planetary physics, in *Shock Compression of Condensed Matter - 1995*, edited by S. C. Schmidt and W. C. Tao, pp. 3-8, AIP Press, Woodbury, NY, 1996.
24. Chen, G. Q., and T. J. Ahrens, Erosion of terrestrial planet atmosphere by surface motion after a large impact, *Physics or Earth and Planetary Interiors*, 1996.
25. Love, S., and T. J. Ahrens, Catastrophic impacts on gravity dominated asteroids, *Icarus*, *124*, 141-155, 1996.
26. Newman, W., E. M. D. Symbalisty, T. J. Ahrens, E. Jones, and A. Chaikin, Impact events and the erosion of planetary atmospheres: Some surprising results from theory and simulation, *Icarus*, [Submitted], 1996.
27. Roulston, M., and T. J. Ahrens, Impact mechanics and frequency of SL9-type events on Jupiter, *Icarus*, 1996.
28. Takata, T., and T. J. Ahrens, Impact of Comet Shoemaker-Levy 9-Size, origin, and plumes-comparison of numerical analysis with observations, *Icarus*, [Submitted], 1996.
29. Ahrens, T. J., T. Takata, and J. D. O'Keefe, Comet Shoemaker-Levy-9 Impact on Jupiter, in *Shock Waves, Proceedings of the 20th ISSW*, 2, edited by B. Sturtevant, et al., pp. 1455-1460, World Scientific, 1997.
30. Bottke, W. F., Jr., D. C. Richardson, and S. G. Love, Can tidal disruption of asteroids make crater chains on the Earth and Moon?, *Icarus*, submitted, 1997.
31. Farley, K. A., S. G. Love, and D. B. Patterson, Atmospheric entry heating and helium retentivity of interplanetary dust particles, *Geochim. Cosmochim. Acta*, submitted, 1997.
32. Keil, K., D. Stöffler, S. G. Love, and E. R. D. Scott, Constraints on the role of impct heating and melting in asteroids, *Meteoritics and Planetary Science*, in press, 1997.
33. Love, S., and T. J. Ahrens, Origin of asteroid rotation rates in catastrophic impacts, *Nature*, [in press], 1997.